A Simplified Delay-Guaranteed Traffic Engineering Method

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***Abstract*—As the streaming of multimedia-rich contents such as videos and music is an increasingly popular Internet service, more traffic flows require real-time performance. For this reason, Traffic Engineering (TE) with consideration of real-time traffic delay requirements is essential to accommodate traffic effectively and lower the link congestion occurrence rate. Most previous studies used equations that require traffic changes also in real-time traffic flows when traffic changes require re-calculation of the routes and did not overcome the risk of degrading transmitted data quality. In this paper, we examine the Simplified Delay-guaranteed Traffic Engineering Method (SDG-TE), which allows us to use TE only for traffic that has no delay requirements and use shortest routes for real-time traffic flows without recalculation even if traffic changes occur. We assume that the total traffic contains is a certain amount of real-time traffic. Simulations show that SDG-TE eliminates route change risks for real-time traffic and real-time traffic can be accommodated effectively without major degradation unlike TE-based traffic schemes. Also, evaluations on the traffic accommodation ability of SDG-TE under the assumption that there some traffic distributions can be predicted suggest that if we assign an adequate volume of real-time traffic, SDG-TE can realize networks with shortest routes that carry 90 percent or more of each maximum traffic volume that can be accommodated.**

***Index Terms*—traffic engineering, shortest path, delay guarantee, performance optimization.**

I. INTRODUCTION

As broadband access technologies have been advanced and the number of users has increased, the traffic volume in core networks is rapidly increasing. The Multi-Protocol Label Switching (MPLS) technology [1] is one of the network engineering technologies that can efficiently accommodate such increased traffic. Among MPLS technologies, Traffic Engineering (TE) is often used to control networks; it distributes traffic across links within the network to avoid link congestion [2]. This traffic distribution allows more traffic can be accommodated efficiently within the network. In other words, more traffic can be accommodated in the same network resource, which makes it possible to offer cheaper services to users.

We note that IP network is becoming the integrated infrastructure for advanced services; it is being used to meet demands for diversified Internet applications such as real-time videos, Voice over IP (VoIP), and electric trading. Those Internet applications require high-quality services which are specified by their Quality of Service (QoS); routes need to be set considering QoS attainment [3],[4]. Specifically, the important characteristic of the traffic streams carrying these rich contents such as videos is the delay. End-to-end transmission delay time cannot exceed a certain value.

As just described, when designing and managing networks, we have to satisfy the delay requirement of real-time traffic and determine routes that can accommodate traffic as much as possible while minimizing the congestion ratio. The issue of setting routes by using TE with delay conditions has been addressed [5]. In the study, they used the number of links, i.e. maximum Hop count, as the delay requirement, and compared the congestion ratios of two cases, one calculated with TE without delay requirements and one with them. They also evaluated much they had to ease the requirements until the congestion ratio with delay requirements became equivalent to the one without the requirements. In another study, researchers divided traffic into two groups, one with shortest routes and one with TE, based on OSPF [7], [8], and tried to minimize the congestion ratio [6].

Reference [5] suggested that ideal congestion ratios can be realized by easing the delay requirements slightly. However, they used a heuristic method with off-line processing in the study, so the method would have difficulty in responding quickly enough to the frequent changes in real-time traffic. Another problem is that delay requirements were the only restriction used in setting routes in the study, the route to be used will be changed when recalculation is triggered by traffic changes, and quality degradation may occur following changes to traffic that has QoS requirements. In Reference[7], the proportion of traffic transferred with MPLS is used as a variable, and it is stated that the method minimizes TE-based traffic. However, the study did not deal with delay requirements, and so it cannot be adapted for accommodating real-time traffic.

The issue of accommodating maximum traffic assuming that

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the traffic has QoS requirements is discussed in [9]. In the study, the researchers maximized the bandwidth, and under the assumption that the bandwidth is to be held at the maximum value, they tried to maximize the volume of TE-based traffic.

However, the study considered QoS traffic that uses network resources at the maximum value and did not consider QoS traffic demand itself. That means that the study does not support realistic issues including the case wherein a certain proportion of the total traffic is QoS traffic.

In this paper, we focus on reducing the real-time traffic quality degradation and simplifying route setting. We use a approach that does not require route changes even if traffic changes. As for routes, we use fixed shortest routes to carry real-time traffic from the point of view that delay conditions exist but should be minimized and it is easier to implement because routes can be determined by a simple algorithm. We also guarantee a certain proportion of real-time traffic to the total traffic while keeping traffic distribution between nodes. Best-effort traffic, other than real-time traffic, is to be accommodated by TE calculation. We evaluate the validity of this method by clarifying how much the congestion ratio can be lowered with TE and how much it influences traffic accommodation ability.

In this paper, Section II describes the LP formulation of network issues considering real-time traffic delay requirements while the proposed method is explained in Section III. We described its evaluation in Section IV and show simulation results in Section V. Section VI reviews the results and our conclusion is stated in Section VII.

II. FORMULATIONS FOR REAL-TIME TRAFFIC WITH DELAY REQUIREMENT

A. Network Description and Formulation of TE

Considering networks with flexible route setting such as MPLS, we assume that traffic between nodes is transferred through a route set that can be set explicitly. It is described below as a linear programming network issue.

Figure 1 shows a network model. Network *G(V,E)* is defined with node set *V* and link set *E* as shown follow.

i,j	nodes
(i,j)	directional link between node i and node j
c_{ij}	capacity of link (i,j)
k, K	each traffic demand and a set of traffic ($k \in K$)
d_k	bandwidth of traffic demand k
s_k, t_k	start node and target node of traffic k
X_{ij}^{k}	ratio of traffic k transmitting through link (i,j)
D_{ij}	delay of link (i,j)

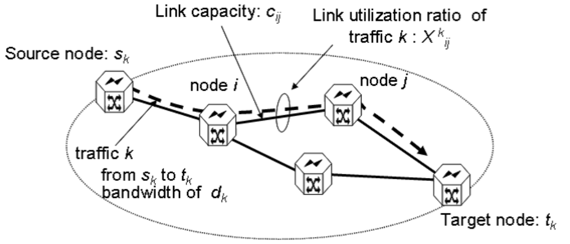


Fig. 1. MPLS backbone network.

Optimization with TE is a technology that distributes traffic within network and smoothes link utilization ratios. This can be realized by minimizing the congestion ratio, *α*, which is the largest value among the link utilization ratios.

The formulation is shown below [12]

$$\min \alpha \tag{1}$$

s.t.

$$\sum_{j:(i,j)\in E} X_{ij}^{k} - \sum_{j:(i,j)\in E} X_{ji}^{k} = \begin{cases} 1, & i = s_k \\ 0, & i \neq s_k, t_k \end{cases} \quad \forall k \in K \tag{2}$$

$$\sum_{k\in K} d_k X_{ij}^{k} \leq \alpha c_{ij}, \quad \forall (i,j)\in E \tag{3}$$

$$\alpha \geq 0,\ 0 \leq X_{ij}^{k} \leq 1,\quad \forall k\in K,\ \forall (i,j)\in E \tag{4}$$

. In this equation, *α* is minimized under the condition that each link utilization ratio is α or smaller after dividing the total traffic volume, $\Sigma_{k\in K}\, d_k\, X_{ij}^{k}$, by c_{ij}. $\Sigma_{k\in K}\, d_k\, X_{ij}^{k}$ is the total amount of traffic flowing in link *(i, j)*, the individual traffic flows are given by d_k. Calculation with TE brings out the congestion ratio, *α*, and traffic accommodating route X_{ij}^{k} that realizes *α*. Equation follows the conservation law of flow, which implies that X_{ij}^{k} is a variable that defines the flow route [10]. We do not describe the formulation that contains t_k here because it is redundant [11]. Equation (3) is the conditional expression that makes the link utilization ratio *α* or smaller.

B. Real-time traffic delay condition

Each traffic d_k consists of real-time traffic d_k^{real} and best-effort traffic d_k^{be}. We assumed the proportion of real-time traffic is *ρ*, the same for each traffic value. Variables that indicate the routes in which d_k^{real} $(=\rho d_k)$ and $d_k^{be}$$(=(1-\rho)d_k)$ flow are Y_{ij}^{k} and Z_{ij}^{k}, respectively. Then if the maximum acceptable real-time traffic delay is D_{max}, the following formulation is true for the propagation delay in link *(i,j)* with D_{ij}.

s.t.

$$X_{ij}^{k}=\rho Y_{ij}^{k}+(1-\rho)Z_{ij}^{k},\ k\in K,\ \forall(i,j)\in E \tag{5}$$

$$\sum_{(i,j)\in E} D_{ij}Y_{ij}^{k} \le D_{\max},\ k\in K,\quad \forall(i,j)\in E \tag{6}$$

If Y_{ij}^{k} has real value other than {0, 1}, real-time traffic ρd_k flow is splitted, which means that real-time traffic flow on multiple routes that have no splitting. In this case, note that equation (6) becomes a condition regarding each route's average delay and it may create routes that do not satisfy the delay requirements. In this case, the delay requirement is implemented by satisfying equation (6) for each route that makes up Y_{ij}^{k}.

III. PROPOSAL OF SIMPLIFIED DELAY-GUARANTEED TRAFFIC ENGINEERING METHOD (SDG-TE)

Previous studies considered optimizing the congestion ratio and maximizing traffic that can be accommodated by giving flexibility within the range in which equation (6) is satisfied to variable Y_{ij}^{k}. This method, however, has a problem because Y_{ij}^{k} is also recalculated when routes are recalculated after traffic demand changes, and that causes changes in real-time traffic routes. As a result, quality degradation such as packet loss and order reversal can be triggered.

In this paper, we propose the Simplified Delay-guaranteed Traffic Engineering Method (SDG-TE), which guarantees real-time traffic delay and avoids the problems.

A. Assumption of real-time traffic

We assume that "all shortest routes in the network between start and target nodes satisfy the delay requirements" for traffic demand. That means that when the shortest routes are used, real-time traffic delay requirements can be always satisfied.

B. Accommodation via SDG-TE

Because IEEE will do the With SDG-TE, traffic is accommodated as described below.

1) Accommodate real-time traffic using the shortest routes.
2) Use the remaining bandwidth to accommodate best-effort traffic with TE.

With this approach, even if changes occur in traffic demand over time, real-time traffic always uses the shortest route with no real-time traffic route changes, which means that there is no risk of quality degradation caused by route changes.

On the other hand, route recalculation based on TE is carried out for best-effort traffic to minimize the congestion ratio, so that route changes can occur.

C. Calculation

First, accommodate traffic d_k^{real} on the shortest routes and then accommodate traffic d_k^{be} on the routes recalculated with TE.

Real-time traffic accommodation:

The variable Y_{ij}^{k} for the route of d_k^{real} can be acquired as follows.

$$\min \sum_{k\in K}\sum_{(i,j)\in E} D_{ij}Y_{ij}^{k} \tag{7}$$

s.t.

$$\sum_{j:(i,j)\in E} Y_{ij}^{k} - \sum_{j:(i,j)\in E} Y_{ji}^{k} = \begin{cases} 1, & i=s_k \\ 0, & i\ne s_k,t_k \end{cases} \quad \forall k\in K \tag{8}$$

$$0\le Y_{ij}^{k}\le 1,\quad \forall k\in K,\ \forall(i,j)\in E \tag{9}$$

Real-time traffic flowing on link (*i,j*) is $\Sigma_{k\in K}\,\rho d_k\, Y_{ij}^{k}$. In this method, only shortest routes are to be used for real-time traffic. In Section II-B, we mentioned that the delay requirements for each route that makes up Y_{ij}^{k} must be satisfied when a real-time traffic route consists of multiple routes. However, we use only shortest routes here, so even if multiple routes exist, all routes should be shortest routes and each satisfies the delay requirements.

Best-effort traffic accommodation:

Variable Z_{ij}^{k} that determines the route accommodating d_k^{be} can be acquired by the following optimization. Here, Y_{ij}^{k} in equation (12) is a constant number and uses the value acquired by minimization of equations (7) to (9).

$$\min\ \alpha \tag{10}$$

s.t.

$$\sum_{j:(i,j)\in E} Z_{ij}^{k} - \sum_{j:(i,j)\in E} Z_{ji}^{k} = \begin{cases} 1, & i=s_k \\ 0, & i\ne s_k,t_k \end{cases} \quad \forall k\in K \tag{11}$$

$$\sum_{k\in K}\rho d_k Y_{ij}^{k} + \sum_{k\in K}(1-\rho)d_k Z_{ij}^{k} \le \alpha c_{ij}, \tag{12}$$

$$\alpha\ge 0,\ 0\le Z_{ij}^{k}\le 1,\quad \forall k\in K,\ \forall(i,j)\in E \tag{13}$$

$\Sigma_{k\in K}(1\text{-}\rho)d_k Z_{ij}^{k}$ in equation (12) is best-effort traffic that flow on the link (*i,j*).

IV. SDG-TE EVALUATION

For evaluating SDG-TE, we determine its traffic accommodation ability and reduction effect for *α* towards *ρ*.

A. T_{real}^{max} and T_{be}^{max}

We use full mesh traffic matrix as the traffic demand and consider the average value of traffic matrix components. We assume that this distribution is fixed in each evaluation by changing traffic volume. The traffic volume, described as T_{total}, consists of real-time traffic and best-effort traffic. Each value of traffic matrix is determined by setting T_{total}. We assume that real-time traffic volume and best-effort traffic volume are described as T_{real} ($=\rho T_{total}$) and T_{be} ($=(1-\rho)T_{total}$), respectively. Hereafter, those values show average values within the distribution when each traffic volume is considered.

We remark traffic for which $\alpha=1$ is true when $\rho=1$ as T_{real}^{max} and traffic for which $\alpha=1$ is true when $\rho=0$ as T_{be}^{max}, respectively. T_{real}^{max} is the maximum value of traffic volume with the condition of using only the shortest routes, while T_{be}^{max} is the maximum value of traffic volume that the network can accommodate. From this definition, $T_{real}^{max} \leq T_{be}^{max}$ is true. For general topologies, i.e. not special cases such as less flexible topologies, $T_{real}^{max} < T_{be}^{max}$ is true. T_{real}^{max} and T_{be}^{max} are determined from the topology and traffic distribution, and those values are the most important indices in this method. We describe a simulation that focuses on T_{real}^{max} and T_{be}^{max}.

B. Congestion ratio evaluation

α and T_{total} have a linear relationship as shown in Figure 2. The plot in Figure 2 is for $\rho=0, 1$. When $\rho \neq 0, 1$, the relation between α and T_{total} is also linear, the slope remains between the straight lines of $\rho=0$ and $\rho=1$. As α and T_{total} have a linear relationship, even when the relationship between α and ρ is evaluated, we only need to perform one evaluation for each T_{total} evaluation. In this paper, we use T_{real}^{max} as T_{total}.

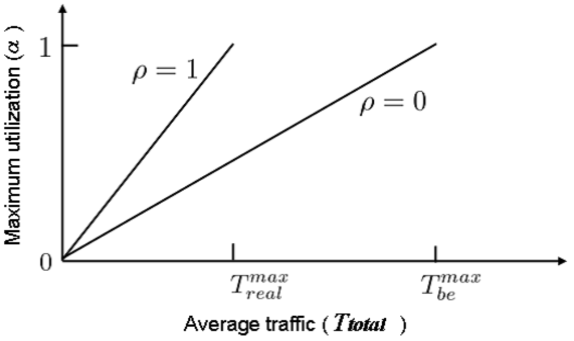


Fig. 2. T_{total} vs. α.

Table I
SIMULATION CONDITIONS.

Topology: realworld	cost239, 11nodes, 25 edges nsfnet, 14 nodes, 21 edges
Topology: brite	25, 50 nodes, Waxman model Node to edge ratio: 2, 3
cost	Distance
Traffic distribution	Average ± 20%

C. Traffic accommodation ability evaluation

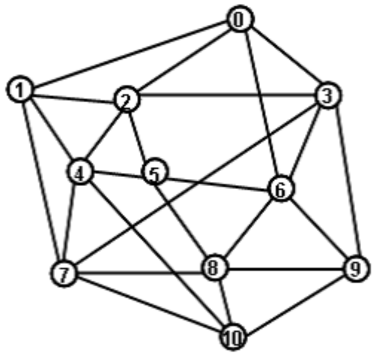
Traffic accommodation ability is the maximum traffic for which $\alpha=1$ or smaller, and, at the maximum, $\alpha=1$ is true. In SDG-TE, since we use only shortest routes for real-time traffic, the flexibility of traffic routes that can be used is small compared to TE which has no restriction. We evaluate here the impact of this on traffic accommodation. Note that it is desirable to accommodate as much real-time traffic, QoS traffic, as possible. The maximum traffic volume that can be accommodated when $\rho=0$ is true is T_{be}^{max}, and when $\rho=1$ is true, it is T_{real}^{max}. So, it is impossible to acquire the maximum values for both at the same time. Therefore, we assumed that the best value of ρ to optimize both traffic volumes lies between 0 and 1. ρ is the proportion of real-time traffic to total traffic, which is originally determined from a demand estimation and operational status, but we consider it here as the value that realizes the maximum traffic accommodation and evaluate the accommodation ability with this value.

V. SIMULATIONS

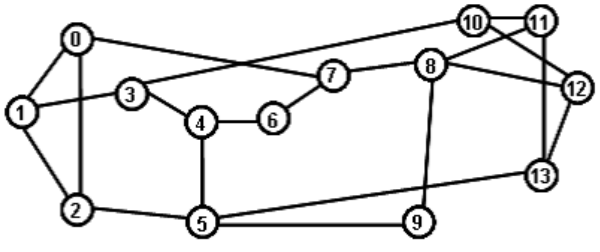
A. Simulation conditions

Table I shows the conditions used in the simulations. As for topologies, we used the real network model of cost239[13], nsfnet[14] shown in Figure 3 and topologies generated by the topology generator brite[15]. [1] We used links with the same capacity. For the delay on each link (i,j), we refer to the distance between real existing cities for the real network model. As for brite, we used the distance output by brite. We used the traffic demands on a full mesh between each node, and randomly changed the distribution within the range of average ±20%.

For cost239 and nsfnet, we generated 10 traffic distributions for each topology. As for the brite-generated topologies, we generated 10 kinds (with 25 nodes) and 8 kinds (with 50 nodes) using the same generation parameter and randomly generated traffic distributions.



(a) COST239



(b) NSFNET

Fig. 3. Eamples of Real World Topologies.

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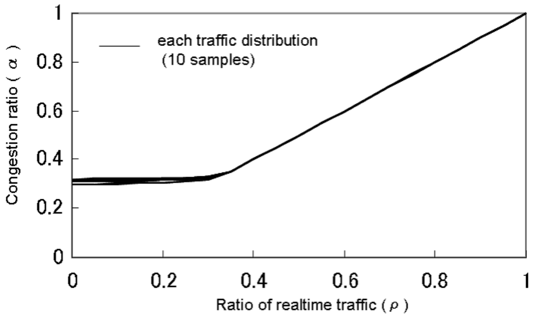
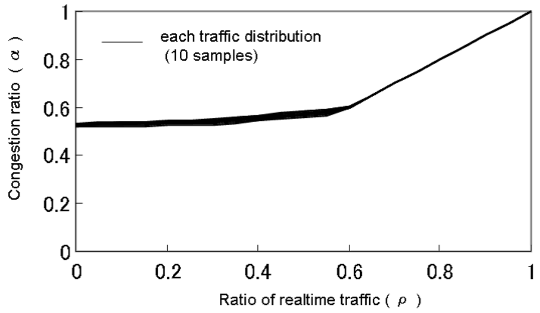
[1] For each topology generated by brite, the number of links equals the number of nodes multiplied by the node to edge ratio.

B. The relation between α and ρ

Figure 4 shows simulation results for cost239 and nsfnet. The vertical axis is the congestion ratio is α and the horizontal axis is ρ. Each line corresponds to results of 10 randomly set traffic distributions. It shows that α=ρ is true, when both topologies have an area wherein ρ has a value equal to or greater than 0.35 in cost239 or 0.6 in nsfnet. α is approximately constant in the area where ρ has smaller values. It also indicates that the dependency on traffic distribution is small. It shows both topologies have an area that α=ρ where ρ is greater than 0.35 for cost239 , 0.6 for nsfnet, respectively. α is approximately constant in the area where ρ has smaller value. It also indicates that the dependency on traffic distribution is small.



(a) COST239

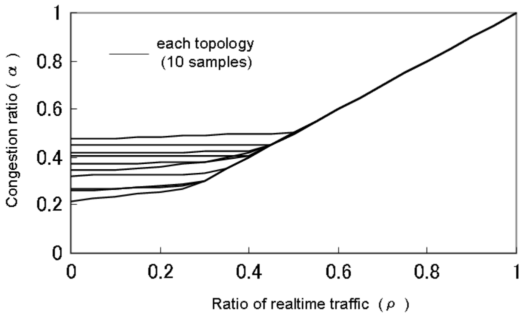


(b) NSFNET

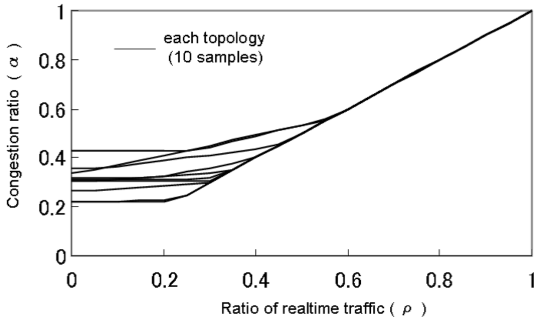
Fig. 4. Ratio of realtime traffic to the total one, ρ vs. congestion ratio α: realworld network topologies.

Figure 5 shows the results for brite-generated topologies. Each line in the Figure corresponds to the multiple topologies generated by brite using the same parameters. The case wherein the number of nodes is 25 and the node to edge ratio is 2 is labeled "wax 25-2." In this case, it also indicates that α=ρ is true where ρ has greater value. The area is, for most cases, occurs when ρ is 0.5 or 0.6 or greater. It seems that these characteristics depend on the differences among each generated topology itself rather than the topology generating conditions. α is approximately constant in the area where ρ has smaller values. Compared to Figure 4, changes are seen in the values of α towards ρ even in this area for some topologies. However, those changes are relatively small compared to the area where ρ has greater value.

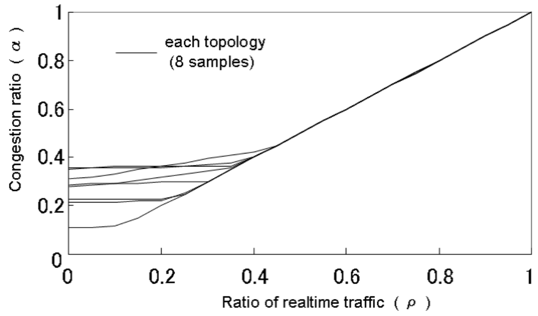
In this SDG-TE evaluation, because traffic volume T_{real}^{max} , i.e. $\alpha=1$ is true when $\rho=1$ is true, is accommodated, α has always the value of ρ or greater. At the same time, the minimum α is α_{TE} or greater is true when T_{real}^{max} is accommodated with TE in order to minimize α. This α_{TE} has the value of α when T_{real}^{max} is accommodated under the condition that ρ is 0. With this meaning, although there are some increases near the point that the straight lines of α=ρ and α=α_{TE} cross, it can be said that we acquired fairly good results in terms of lowering the value of α to its limit.



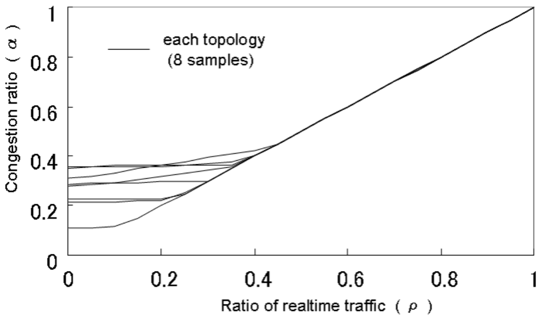
(a) wax25-2



(b) wax25-3



(c) wax50-2



(d) wax50-3

Fig. 5. Ratio of realtime traffic to the total one, ρ vs. congestion ratio α: brite generated topologies.

C. ρ setting in evaluation of traffic that can be accommodated

We evaluate the amount of traffic that can be accommodated. We first give ρ and acquire traffic that can be accommodated and real-time traffic under that condition, and then compare the result to ideal maximum values of T_{be}^{max} and T_{real}^{max}.

It is better to accommodate traffic that is closer to T_{be}^{max} and real-time traffic that is closer to T_{real}^{max}. The closer ρ is to 1, the greater is the real-time traffic volume that can be accommodated. On the other hand, the closer ρ is to 0, the greater is the network traffic volume that can be accommodated. Here, we consider the best ρ for optimizing both traffic volumes.

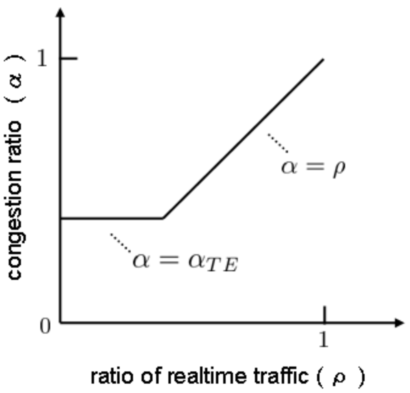


Fig. 6. Typical relation between α vs. ρ.

The relationship between α and ρ shown in Figure 4 and Figure 5 is similar to that in Figure 6. α is equal to ρ in the area where ρ is greater, while α tends to stay constant in the area where ρ is smaller. That is, the value when $\rho=0$ and the congestion ratio α_{TE} yielded by using TE to accommodate total traffic T_{real}^{max}. Then, considering the characteristics in Figure 6, we determined the optimum ρ that maximizes the network traffic and the real-time traffic that can be accommodated.

In the area where α equals ρ, the accommodable total traffic when the proportion of real-time traffic is ρ, $T_{MAX,\,\rho}$, is T_{real}^{max}/ρ. Thus, real-time traffic volume at this point becomes T_{real}^{max} ($=\rho T_{MAX,\,\rho}$). So, as for real-time traffic, it can be accommodated at the maximum value of the traffic volume that can be accommodated originally.

Next, in the area where α stays constant and equal to α_{TE}, since the value α is the same value as when total traffic is accommodated with TE, $T_{MAX,\rho}$ should be equal to T_{be}^{max}. Thus, in the area of this ρ, the total traffic volume that can be accommodated is not influenced and it can be accommodated at the value of the original maximum traffic volume that can be accommodated in the network. At this point, real-time traffic is ρT_{be}^{max}.

As for the characteristics shown in Figure 6, if we set ρ to α_{TE}, the total traffic volume that can be accommodated does not decrease and the real-traffic volume that can be accommodated is maximized.

As for real characteristics, α tends to have greater values than α_{TE} and ρ approaches α_{TE}, however, in terms of maximizing the traffic volume that can be accommodated, $\rho=\alpha_{\mathrm{TE}}$ is the optimum setting. Considering that, we compared the total traffic $T_{MAX,\rho=\alpha TE}$ and real-time traffic $\rho T_{MAX,\rho=\alpha TE}$ at each maximum value of T_{be}^{max} and T_{real}^{max}, and found that $T_{MAX,\rho=\alpha TE}$ / T_{be}^{max} $=\rho T_{MAX,\rho=\alpha TE}$ / T_{real}^{max}. This means that, in reality, we only need to acquire either the total traffic or real-time traffic. We remark this dimensionless value as $T_{MAX,\rho=\alpha TE}$.

Table II

TRAFFIC ACCOMMODATION WHEN $\rho=\alpha_{TE}$: REALWORLD TOPOLOGIES.

(a) cost239

ρ (= α TE)	0.296	0.310	0.312	0.300	0.311	0.320	0.314	0.317	0.318	0.315	0.311 (av.)
$T^{\max}_{\rho=\alpha\mathrm{TE}}$	0.930	0.944	0.954	0.938	0.953	0.939	0.957	0.957	0.938	0.965	0.948 (av.)

(b) nsfnet

ρ (= α TE)	0.532	0.531	0.530	0.531	0.528	0.524	0.527	0.535	0.533	0.516	0.529 (av.)
$T^{\max}_{\rho=\alpha\mathrm{TE}}$	0.926	0.942	0.913	0.910	0.910	0.909	0.929	0.920	0.939	0.917	0.922 (av.)

Table III

TRAFFIC ACCOMMODATION WHEN $\rho=\alpha_{TE}$: BRITE GENERATED TOPOLOGIES.

(a) wax25-2

ρ (= α TE)	0.342	0.269	0.323	0.479	0.219	0.406	0.371	0.448	0.418	0.259	-
$T^{\max}_{\rho=\alpha\mathrm{TE}}$	0.892	0.919	0.968	0.957	0.836	1.000	0.910	1.000	0.985	0.920	0.939 (av.)

(b) wax25-3

ρ (= α TE)	0.222	0.309	0.265	0.357	0.340	0.315	0.305	0.219	0.305	0.428	-
$T^{\max}_{\rho=\alpha\mathrm{TE}}$	0.994	0.850	0.895	0.842	0.729	0.933	0.963	0.960	0.990	0.855	0.901 (av.)

(c) wax50-2

ρ (= α TE)	0.359	0.353	0.108	0.288	0.309	0.212	0.227	0.282	-
$T^{\max}_{\rho=\alpha\mathrm{TE}}$	0.984	0.945	0.889	0.963	0.780	0.954	0.991	0.828	0.917 (av.)

(d) wax50-3

ρ (= α TE)	0.207	0.180	0.301	0.195	0.181	0.285	0.222	0.165	-
$T^{\max}_{\rho=\alpha\mathrm{TE}}$	0.955	0.932	0.955	0.899	0.896	0.925	0.906	0.997	0.933 (av.)

D. Evaluation results for traffic that can be accommodated

Table II shows $\rho(=\alpha_{\mathrm{TE}})$ and $T_{MAX,\rho=\alpha TE}$ for the real network topologies. The results for cost239 and nsfnet are those for 10 randomly 10 traffic distributions. All values of $T_{MAX,\rho=\alpha TE}$ lie between 0.930 and 0.965 (average 0.948) for cost239 and between 0.909 and 0.942 (average 0.922) for nsfnet. No major difference in traffic distribution was seen with α_{TE} and $T_{MAX,\rho=\alpha TE}$. From this result, we can say that, by setting $\rho=\alpha_{\mathrm{TE}}$, greater than 93 % (cost239) or greater or 90 % (nsfnet) of the maximum traffic volume that can be accommodated when total traffic is accommodated with TE can be accommodated, and 93 % (cost239) or greater or 90 % (nsfnet) of the total traffic volume that can be accommodated with the shortest route.

Table III also shows the results for the brite-generated topologies.[2] Results for 10 topologies for wax25-2, wax25-3 and 8 topologies for wax50-2, wax50-3 are shown. As for $T_{MAX,\rho=\alpha TE}$, 0.729(one example in wax25-3) and 0.780(one example in wax50-2) are small values, however, 0.9 or greater values (average) were acquired for all wax25-2, wax25-3, wax50-2 and wax50-3 topologies. That means that 90% of each maximum accommodating volume of the total traffic and real-time traffic can be accommodated. As for, the wax25-2 topology, one result yielded $T_{MAX,\rho=\alpha TE} = 1$. In this case, traffic can be accommodated on shortest routes at the maximum level and on the network at the maximum level as well.

We showed examples only for $\rho=\alpha_{\mathrm{TE}}$ in Tables II and III, but other than those values, $T_{MAX,\rho=\alpha TE} / T_{be}^{max}$ did not match $\rho T_{MAX,\rho=\alpha TE} / T_{real}^{max}$. When ρ approached 1, the former became smaller, and the latter approached 1 and eventually became 1 when $\rho=1$. Also, when $\rho=1$ approached 0, the latter became smaller and the former approached 1 and eventually became 1 when $\rho=0$.

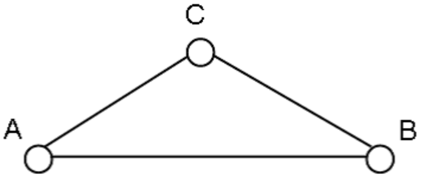


Fig. 7. Example topology.

VI. EXAMINATION

A. The relation between ρ and α

1) explanation of Figure 6 characteristics with simple example network: We consider an example network shown in Figure 7. We assume that links AB, AC, and CB have the same capacity, value of 1, each link delay is 1, and there is traffic demand of 1 from A to B.[3] The maximum traffic accommodated only on the shortest routes, T_{real}^{max}, is the traffic that can be transmitted using link AB and $T_{real}^{max} = 1.0$. On the other hand, the maximum traffic volume that can be accommodated by using only TE (T_{be}^{max}) is the traffic that was transmitted using AB as well as ACB and $T_{be}^{max} = 2$. When we accommodate the traffic of T_{real}^{max} and change ρ as the parameter, the real-time traffic is reduced after ρ becomes smaller than 1 but best-effort traffic appears. If ρ is large but best-effort traffic is minor, this traffic can be accommodated using the ACB route without raising the congestion ratio larger than ρ. If we lower ρ under 1, α continues to be fall until $\rho=0.5$. When $\rho=0.5$ is true, $\alpha=0.5(=\alpha_{\mathrm{TE}})$ is also true. However, when ρ becomes smaller than 0.5, the value of ρ stays at 0.5. Since T_{real}^{max} is 1 and $\rho=1$, $\alpha=0.5$ is true when all traffic is accommodated with TE, α cannot be smaller than 0.5. Thus, the range where $\alpha=\rho$ i.e. characteristics shown in Figure 6, suggests that best-effort traffic generated by setting ρ smaller than 1 can be accommodated within the range that the link utilization ratio maximum value does not exceed ρ. Although the size of this range depends on the simulation conditions and it cannot be said that the range is assured of existing, it was present in all the simulation examples considered here.

2) The range where $\alpha=\rho$: When $\rho=1$ is true, $\alpha=\rho(=1)$ becomes true. We assumed that $\alpha=\rho$ became true when $\rho=\rho_1$ ($\neq 1$) and examined values of α within the range where $\rho_1 < \rho < 1$ is true. When best-effort traffic T_{be} is to be accommodated after real-time traffic T_{real} is accommodated; the unused bandwidth in each link is calculated by subtracting the bandwidth occupied by T_{real} from each bandwidth, c_{ij}. Since the route that T_{real} passes is fixed, the bandwidth subtracted is proportional to ρ, and the proportionality factor is described as γ_{ij}. γ_{ij} is the value to be determined by the route that T_{real} uses and depends on each link (i,j). Under the condition $\rho=\rho_1$, at the point T_{real} is accommodated, the unused bandwidth of each link becomes $c_{ij} -\gamma_{ij}\rho_1$. γ_{ij} has the same unit of c_{ij}, $c_{ij} \geq \gamma_{ij}$ is true. The unused bandwidth was 0 at least on one link when $\rho=1$, and $c_{ij} =\gamma_{ij}$ on this link. $\alpha=\rho_1$ means that it was able to use each link's remaining bandwidth $c_{ij} -\gamma_{ij}\rho_1$ within the range that the maximum link utilization ratio did not exceed ρ_1, and accommodated T_{be} (= $(1 - \rho_1) T_{total}$) by preventing the maximum link utilization ratio from exceeding ρ_1. In other words, $(1 - \rho_1) T_{total}$ traffic on each link can be accommodated by using $\rho_1(c_{ij} -\gamma_{ij})$ or a smaller bandwidth. Next, we examined if ρ becomes ρ_2 that is greater than ρ_1. In this case, the remaining bandwidth becomes $c_{ij} -\gamma_{ij}\rho_2$. T_{be} to be accommodated is $(1 - \rho_2) T_{total}$. α becomes $\rho(=\rho_2)$ or greater by accommodating T_{real}, but if T_{be} can be accommodated by using only $\rho_2(c_{ij} -\gamma_{ij})$ or lower bandwidth in each link, all link utilization ratios are ρ_2 or lower and $\alpha=\rho_2$. Now we examined the traffic accommodation for ρ_2, by using the results calculated under the condition of ρ_1 as the traffic accommodation route. Since the best-effort traffic volume is calculated using the factor of $(1 -\rho_2)/(1 -\rho_1)$, it can be accommodated if each link has the bandwidth of $\rho_1(c_{ij} -\gamma_{ij})(1 -\rho_2)/(1 -\rho_1)$. Next, $\rho_1 < \rho_2 \leq 1$, $c_{ij} \geq \gamma_{ij}$ leads to $\rho_1 (c_{ij} -\gamma_{ij})(1 -\rho_2)/(1 -\rho_1) \leq \rho_2 (c_{ij} -\gamma_{ij})$ which means that under the condition of $\rho=\rho_2$, the unused link bandwidth after accommodating T_{real} is greater than the link bandwidth that yields the maximum link utilization ratio of ρ_2 or less after accommodating T_{be}. Thus, if $\alpha=\rho$ is true for ρ_1 (< 1), for all ρ in the range of ρ_1 up to or equal to 1, it is clear that $\alpha=\rho$.

3) The range where $\alpha=\alpha_{TE}$: If $\alpha=\alpha_{TE}$ is true at ρ_3 ($\rho\neq 0$), then $\alpha=\alpha_{TE}$ is always true for ρ up to ρ_3. It is because using the smallest value of α_{TE} and the route calculated value for ρ that is equal to or smaller to ρ_3 offers more flexibility than the route calculation using ρ_3. Thus, if $\alpha=\rho$ is true when $\rho\neq 1$, there should be an area wherein $\alpha=\rho$ is true, while there should be an area where α is a constant value, α_{TE}. The value of α_{TE} is mostly determined by the network's topology.

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[2] Table II shows the average values of both α_{TE} and $T_{MAX,\rho=\alpha TE}$ because each topology had similar characteristics. Table III shows no average value as the topology dependency was great.

[3] Units are abbreviated here.

B. *Preferable usage condition of SDG-TE*

We consider that the network should be designed to accommodate traffic demand that is estimated using a predefined α. On such a network, we can accommodate the traffic volume as real-time traffic on the shortest routes up to the as proportion of α_{TE} without blocking traffic demands. Thus, we can say that SDG-TE functions most effectively when the proportion of real-time traffic does not exceed the network's α_{TE}.

VII. CONCLUSION

In this paper, we proposed SDG-TE as a simple TE method for QoS traffic. SDG-TE accommodates real-time traffic in shortest routes, while other traffic is accommodated by TE as best-effort traffic. SDG-TE has the following characteristics. (1) No route changes are required for real-time traffic even though it is assured of excellent QoS. (2) It lowers the congestion ratio through the use of TE. (3) The proportion of the real-time traffic to the total traffic determines the volumes of real-time traffic and network traffic can be accommodated. By setting an adequate proportion of real-time traffic, the volume of network traffic and real-time traffic that can be accommodated at the same time can be increased. We compared the traffic volume that can be accommodated when only TE is used and when only shortest route is used. As a result, about 90% or greater of the maximum traffic volume could be realized at the same time. (4) SDG-TE functions most effectively when the proportion of real-time traffic does not exceed the network's α_{TE}. We have proved that TE that considers QoS can be realized simply without losing the benefits of TE. We believe that SDG-TE is also an applicable technique for cases that involve QoS-related costs [16] other than distance.

REFERENCES

[1] E. Rosen, A. Viswanathan, and R. Callon, "Multiprotocol Label Switching Architecture," IETF, RFC 3031, January 2001.

[2] D. Awduche, J. Malcolm, J. Agogbua, M. O'Dell, and J. McManus, "Requirements for Traffic Engineering Over MPLS," IETF, RFC 2702, September 1999.

[3] E. Crawley, R. Nair, B. Rajagopalan, H. Sandick, "Framework for QoS-based Routing in the Internet," IETF, RFC 2386, 1998.

[4] S. Blake, D. Black, M. Carlson, E. Davies, Z. Wang, and W. Weiss, "An architecture for diffrentiated services," IETF, RFC 2475, 1998.

[5] Y. Lee, Y. Seok, and Y. Choi, "Traffic Engineering with Constrained Multipath Routing in MPLS Networks," IEICE TRANS., COMMUN., Vol.E87-B, No.5, pp.1346-1356, 2004.

[6] M. Zhabg, B. Liu, and B. Zhang, "Multi-Commodity Flow Traffic Traffic Engineering with Hybrid MPLS/OSPF Routing," IEEE Globecom 2009, pp.1077-1083, PID973525, 2009.

[7] J. Moy, "OSPF version 2," RFC 2328, April 1998.

[8] K. Kompella, Y. Rekhter, "OSPF Extensions in Support of Generalized Multi-Protocol Label Switching (GMPLS)," IETF, RFC 4203, 2005.

[9] D. Mitra and K. G. Ramakrishnan, "A Case Study of Multiservice, Multipriority Traffic Engineering Design for Data Networks," IEEE Globecom 1999, Part B, pp.1077-1083, 1999.

[10] R. K. Ahjua, T. L. Magnanti, and J. B. Orlin, "Networks Flows: Theory, Algorithm, and Applications," PRENTICE HALL, 1993.

[11] E. Oki and A. Iwaki, "Performance of Optimal Routing by Pipe, Hose, and Intermediate Models," IEICE Trans. Commun., vol. E93-B, no. 5, pp.1180-1189, May 2010.

[12] Y. Wang, and Z. Wang, "Explicit Routing Algorithms for Internet Traffic Engineering," IEEE ICCCN 1999, pp.582 - 588, 1999.

[13] M. O'Mahony, M. C. Sinclair, and B. Mikac, "Ultra-high capacityoptical transmission network: European research project cost 239," Information,Telecommunications, Automata Journal, vol. 12, pp. 33-45,June 1993.

[14] X. Niu, W. D. Zhong, G. Shen, and T. H. Cheng, "Connection establishment of label switched paths in IP/MPLS over optical networks," Photonic Network Communications, vol. 6, pp. 33-41, July 2003.

[15] http://www.cs.bu.edu/brite/

[16] R. Bhandari, Survivable Networks Algorithms for Diverse Routing, KLUWER ACADEMIC PUBLISHERS, 1999.

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